Supercontinent cycles disrupted by strong mantle plumes

Benjamin R. Phillips
Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
Hans-Peter Bunge
Department of Earth and Environmental Sciences, Ludwig Maximillians University, Munich, D-80333 Munich, Germany

ABSTRACT

A theoretical basis for the regularity of supercontinent cycles is lacking. Here we show that periodic supercontinent cycles are unlikely if thermal instabilities originating at the core-mantle boundary are of sufficient strength. We couple multiple mobile continents with vigorous mantle convection in a spherical geometry. Regular supercontinent cycles lasting 400 ± 50 m.y. occur in idealized models with three continents and a mantle heated purely from within by radioactive decay. In a model incorporating six continents and strong mantle plumes, this regularity is broken and supercontinents form only sporadically. Our results suggest that periodic supercontinent cycles are unlikely to occur in realistic Earth models.

Keywords: supercontinent cycles, mantle convection, plumes, numerical model.

INTRODUCTION

The existence of the supercontinent Pangea 200 Ma was first postulated by Wegener (1924) based on paleontologic, lithologic, and orogenic records, and the familiar similarity of the coastlines of South America and Africa. New geologic and paleomagnetic data have strengthened the hypothesis that multiple supercontinents existed prior to Pangea. The aggregation and dispersal of supercontinents is a fundamental process in Earth evolution. The growth of global mountain belts (Sutton, 1963; Hoffman, 1991), the broad uplift of all of southern Africa (Anderson, 1982), and the stability of the Earth's rotation axis (Li et al., 2004) have all been attributed to the formation of supercontinents and their subsequent influence on the mantle. Flood basalt volcanism is often correlated with supercontinent breakup (Courtillot and Renne, 2003; Condie, 2004). Beyond the realm of solid Earth geophysics and geology, the supercontinent cycle also has important implications for the atmosphere and its climate, chemistry, and biology. Even the severe snowball Earth hypothesis may be related to supercontinents (Kirschvink, 1992; Donnadieu et al., 2004).

Evidence for Neoproterozoic (ca. 1000–700 Ma) Rodinia (Dalziel, 1991; Hoffman, 1991; Moores, 1991) and Paleoproterozoic–Mesoproterozoic (ca. 1800–1500 Ma) Columbia (Rogers and Santosh, 2002; Zhao et al., 2002; Meert, 2002) support the idea that global cycles of continental reorganization have occurred throughout Earth's history. However, constraints on the long-term history of continental motion are limited. Integrated models of the positions of major cratons based on paleomagnetic and geologic grounds only extend back to 750 Ma (Lawver et al., 2004; Fig. 1). By following the proximity of 16 prominent cratons (Fig. 1A) with respect to one another, we constructed a trend representing assembly and breakup during the past 750 m.y. (Fig. 1B). Three peaks in aggregation are evident, corresponding to Rodinia ca. 750 Ma, the short-lived supercontinent Pannotia, hypothesized to have occupied the South Pole in the latest Neoproterozoic (Dalziel, 1997), and Pangea in the late Paleozoic. This narrow picture suggests a time scale of hundreds of millions of years between the breakup and reaggregation of supercontinents.

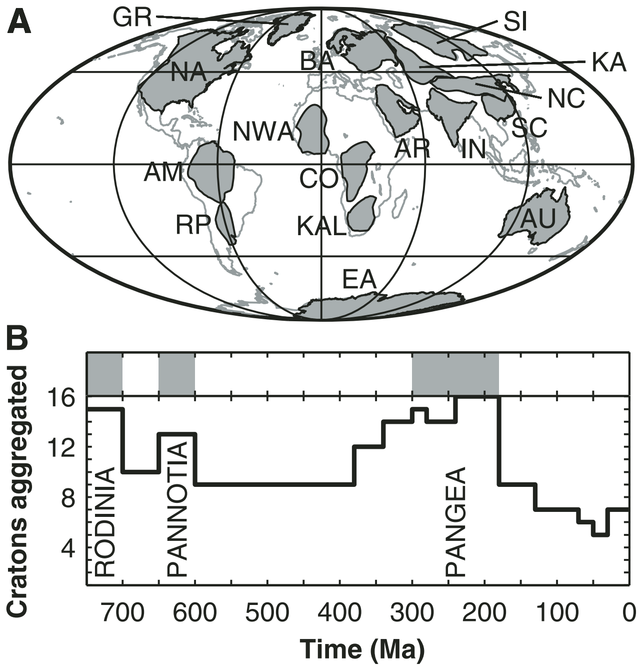

Figure 1. Aggregation of continental cratons since 750 Ma (based on Lawver et al., 2004). A: 16 terranes (shaded gray) considered are Amazonia (AM), Arabia (AR), Australia (AU), Baltica (BA), Congo (CO), East Antarctica (EA), Greenland (GR), India (IN), Kazakhastan (KA), Kalahari (KAL), North America (NA), North China (NC), Northwest Africa (NWA), Rio Plata (RP), South China (SC), and Siberia (SI). Kazakhastan is included only back to 450 Ma. B: Number of cratons aggregated, shown every 50 m.y. from 750 Ma to 550 Ma and then every 10 m.y. to present. Gray shading indicates rough periods of integrity for Rodinia, Pannotia, and Pangea.

The supercontinent cycle implies large-scale (~10,000 km) continental displacements, as documented in paleomagnetic studies (Lawver et al., 2004; Gordon et al., 1979). Geodynamic models predict comparable motion in response to viscous torques imparted on continents by the convecting mantle below (Gurnis, 1988; Zhong and Gurnis, 1993; Phillips and Bunge, 2005). However, the dominant convective length scale in these models, which governs the extent of continental motion, depends on the heat budget of the mantle. In particular, mantle flow reaches global scales when heat entering from the core is negligible (Lowman and Jarvis, 1999; Phillips and Bunge, 2005).

Heat flux from the core into the mantle is secondary to heat generated within the mantle due to the decay of radioactive elements (Wasserburg et al., 1964), though the core contribution is not well defined. Limitations on internal heat sources (Kellogg et al., 1999), the dynamics of the geodynamo (Buffett, 2002), the nonadiabatic nature of the geotherm (Bunge, 2005), and flux estimates based on seismic tomographic images of mantle plumes (Nolet et al., 2006) all suggest that heat flux across the core-mantle boundary could compose as much as 15%–30% of the Earth's heat budget. This is significantly more than the 5%–10% derived from classic measurements of the dynamic topography over hotspots (Davies, 1988). Core heat flux is therefore a fundamental variable, and its effect on the long-term behavior of the continents is not well understood.

MODEL DESCRIPTION

We use the three-dimensional spherical mantle convection model Terra (Baumgardner, 1985), modified to incorporate continents (Phillips and Bunge, 2005). Continents are approximated as buoyant, perfectly insulating spherical caps, the motion of which is determined by balancing the torques applied on their bases by the underlying convective flow (Gable et al., 1991). This work builds on the parameter study of Phillips and Bunge (2005), focusing on the extension to multiple continents. Colliding continents generate equal and opposite repulsive forces, preventing overlap and approximating perfect rigidity (Trubitsyn and Rykov, 2001). Our continents do not stick upon collision and are free to move independently throughout model evolution. Time scales for continental dispersal determined in the models therefore constitute a lower bound on supercontinent lifetime.

While our continents are rigid, the noncontinental, or oceanic, surface regions are governed by a free-slip boundary condition. As a result, our models neglect the potential influence of large oceanic plates on the convective wavelength and temperature of the underlying mantle (Lowman and Gable, 1999). The contribution of plate forces such as slab pull are also absent, as we compute continental velocities based solely on basal tractions and continent-continent interactions. The influence of tectonic plates is an important topic for future study, but we focus here on the role of continents.

Calculations are performed on a mesh containing more than 10×10^6 finite elements, which yields a global grid spacing of 50 km and permits us to model convection at a Rayleigh number of 10^7 (based on internal heating). This is likely lower than that of the Earth by one to two orders of magnitude (Turcotte and Schubert, 2002). Model velocities are therefore smaller, and model times longer, than for the Earth. For our results, we scale these model velocities and hence the model times (Gurnis and Davies, 1986) to a mean surface velocity over the simulation's duration of 5 cm/yr, representative of present-day root mean square (RMS) plate velocities. This scaling is simplified; it neglects secular cooling of the mantle over the 2000 m.y. time scale represented in our models. The decay of radiogenic heat sources has led to an ~5% decrease in the temperature of the mantle since the Proterozoic that, although small, may have had an impact on convective velocities due to the strong temperature dependence of mantle viscosity (Turcotte and Schubert, 2002).

RESULTS

We began with a simple reference model incorporating three continents. This geography is analogous to that following the breakup of Rodinia into East Gondwana, West Gondwana, and Laurasia ca. 700 Ma, as each of these three large continents remained intact until their reaggregation into Pangea ~400 m.y. later. We assume incompressible flow, heat generated purely from within due to the decay of radioactive elements, and a viscosity increase by a factor of 30 from the upper to the lower mantle (Hager and Richards, 1989). The parameter values chosen were based on those used in our previous studies (Bunge et al., 1996; Phillips and Bunge, 2005). To avoid the influence of initial conditions on the results, all calculations were first run until the heat flux across the outer boundary of the model had stabilized.

Figure 2A shows a snapshot of the temperature field for the model described. Each continent, represented by a transparent circular cap, covers 10% of the surface. The right hemisphere is dominated by hot (yellow to red) upwellings under the continents, while the opposite hemisphere harbors mainly cold (green to blue) downwellings. The locations of the continents in this model after 0, 225, and 450 m.y. are plotted in Figure 2B. A supercontinent breaks up, disperses, and then reassembles 450 m.y. later in the opposite hemisphere. Such behavior continues cyclically throughout a 2000 m.y. simulation, as shown in Figure 3A. The number of continents aggregated as a function of time is plotted. There are six peaks, representing supercontinents, spaced in time by ~400 m.y.

The period shown in Figure 3A reproduces the timing of the late Neoproterozoic–Paleozoic supercontinent cycle and that of early two-dimensional models with two continents (Gurnis, 1988). However, this model incorporates only three continents and ignores the influence of active mantle plumes.

To address these simplifications we ran three more realistic models. For model B we first included additional heat input from the core, amounting to 30% of the total mantle heat budget. Next, model C has a purely internally heated mantle, but incorporates six smaller continents, each covering 5% of the surface, similar to present-day North America. We used six continents and 30% core heating for model D. Time series of aggregation and dispersal for these three models are shown in Figures 3B–3D.

Figure 3B shows that the addition of 30% core heating clearly disrupts the 400 m.y. cycle of the purely internally heated, three-continent model (Fig. 3A). Only three irregularly spaced supercontinents form over 2000 m.y. Figure 3C indicates that in the absence of core heating, six continents can still undergo episodes of periodic supercontinent formation and breakup. While there are no supercontinents between ~50 and 1000 m.y., the

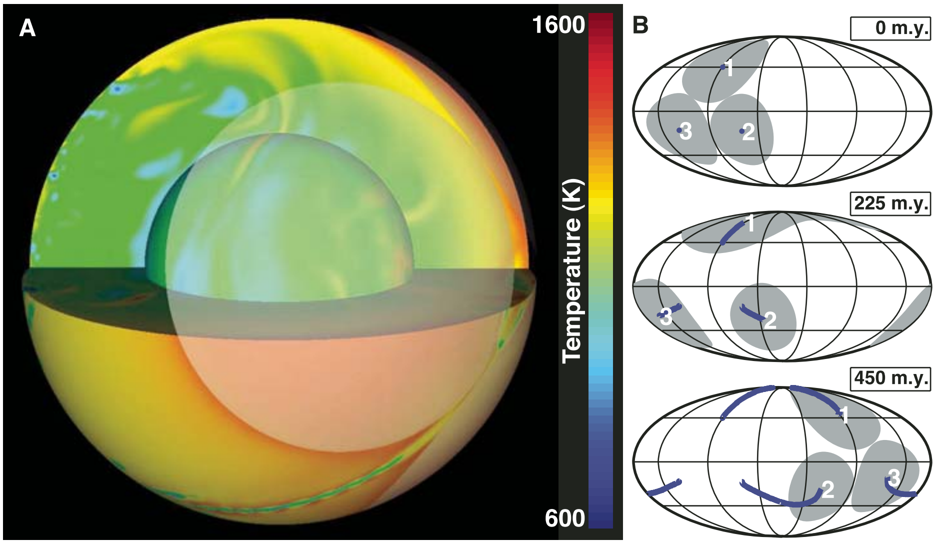

Figure 2. Model with three continents and purely internally heated mantle. Each continent covers 10% of the surface, similar to present-day Asia. A: Snapshot of temperature in the mantle. Continents are shown as transparent caps. Red is hot (upwellings beneath continents) and blue is cold (downwellings away from continents). Outer surface corresponds to 100 km depth. B: Continent locations (gray circles) and drift paths (blue lines) for excerpts from the model. At 0 m.y. the continents are grouped into a supercontinent. By 225 m.y. the continents have dispersed. They reaggregate by 450 m.y. to form a second supercontinent.

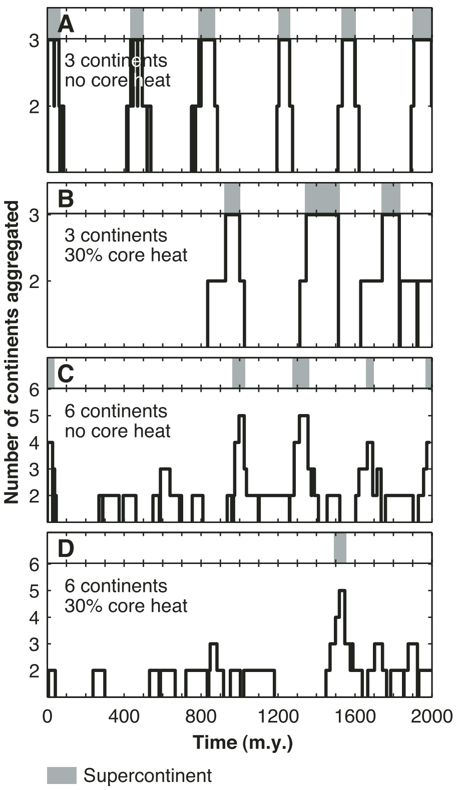

Figure 3. Aggregation and dispersal over 2000 m.y. for four models. Gray shading highlights when three (three-continent models) or four or more (six-continent models) continents are in contact. A: Aggregations for the purely internally heated, three-continent model of Figure 2. Six supercontinents separated by ~400 m.y. formed during the simulation. B: Model identical to A except that 30% of the heat introduced into the mantle comes from the core. There are no longer regular supercontinent cycles. C: Model heated only from within (like A), but with six continents, each covering 5% of the surface, analogous to North America. There are five large-scale aggregations. D: Model with six continents and 30% core heating. Only one supercontinent formed during 2000 m.y.

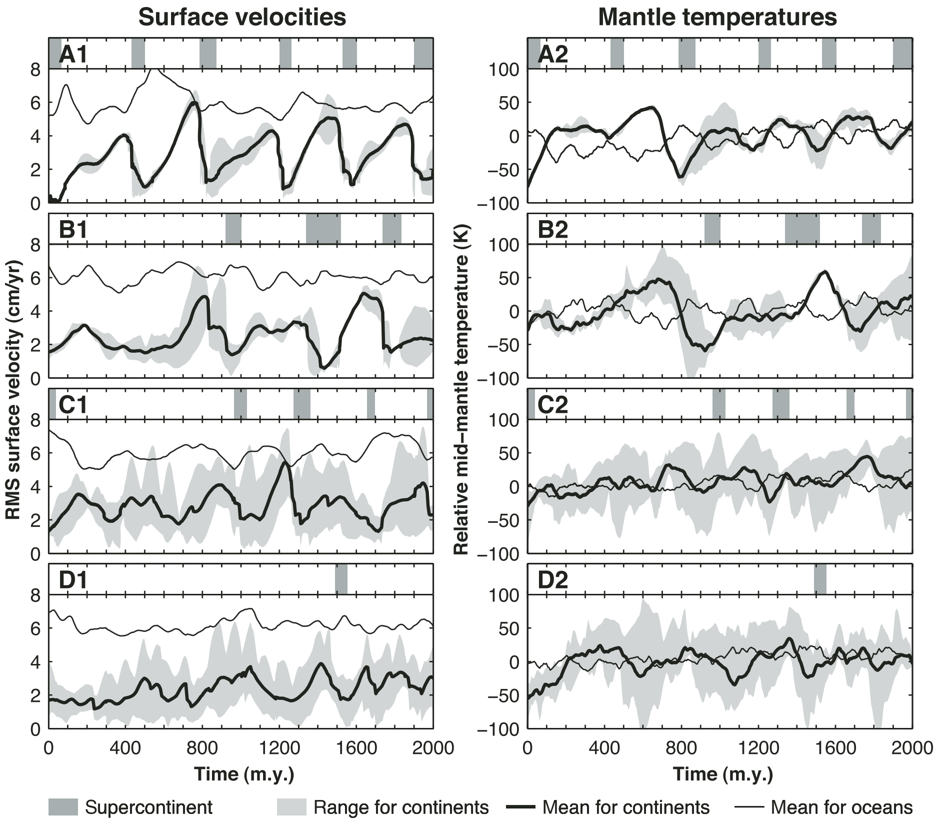

Figure 4. Surface velocity and mantle temperature over 2000 m.y. Dark gray shading is from Figure 3. A1–D1: Range in root mean square (RMS) surface velocities for individual continents (light gray shading), mean RMS velocity for all continents combined (thick line), and RMS velocity for the remainder of the surface, or oceanic region (thin line) for models with pure internal heating or 30% core heating and three continents, and pure internal heating or 30% core heating and six continents, respectively. Peak continental velocities generally occur just before supercontinent aggregations. A2–D2: Range in temperatures at mid-mantle depth beneath continents (light gray shading), mean of those temperatures (thick line), and mean temperature beneath oceanic region (thin line) for models in A1–D1, respectively. Continental aggregations generally occur over temperature minima and lead to subsequent warming of underlying mantle.

last 1000 m.y. of the simulation yields four large-scale aggregations of four to five continents, each with a period of ~350 m.y. In contrast, combining six small continents and 30% core heating almost eliminates the formation of supercontinents. A single five-continent grouping occurs at 1500 m.y. for model D (Fig. 3D).

To explore the feedback between continents and the underlying mantle, we plot RMS surface velocities and mantle temperatures as a function of time for all four models in Figure 4. For three-continent models velocities range from ~0–6.5 cm/yr (Figs. 4A1, 4B1). Peak velocities occur just before supercontinent aggregations (dark gray shading). Model velocities in noncontinental, or oceanic, regions vary between 5 and 8 cm/yr and tend to peak shortly after supercontinent breakup. Individual continents in the six-continent models exhibit bursts in velocity approaching 8 cm/yr that occur on time scales of ~100 m.y. (Figs. 4C1, 4D1).

The evolution of mantle temperature in the models shows that supercontinents aggregate over regions that are anomalously cold by as much as 100 K. Peak-to-peak warming of as much as 100 K then occurs in association with supercontinent dispersal. These correlations are most pronounced for the three-continent models (Figs. 4A2, 4B2). Smaller continents have less effect on the underlying mantle (Figs. 4C2, 4D2). The increase in short period (<100 m.y.) variations in Figure 4D2 reflects the influence of localized mantle plumes impinging on the base of small continents.

DISCUSSION AND CONCLUSIONS

The three-continent, purely internally heated, case is a simplified model that demonstrates the potential for strong feedback between continents and convection. Figures 4A1 and 4A2 show that the continents are driven rapidly toward regions of cold mantle, representing dominant downwellings. The continents then insulate the underlying mantle, allowing its temperature to rise. Other modeling studies also show the development of broad, hot upwellings beneath large surface plates overlying a dominantly internally heated mantle (Lowman and Jarvis, 1999; Yoshida et al., 1999; Phillips and Bunge, 2005). This global-scale flow drives the aggregation and dispersal of antipodal supercontinents in reference model A.

Strong mantle plumes associated with 30% core heating disrupt the regular formation of supercontinents in our models, even for a three-continent system (Fig. 3B). This is not surprising, as continents were previously found ineffective in organizing flow originating at the core-mantle boundary (Phillips and Bunge, 2005). In addition, observations suggest that smaller continents undergo more time-dependent motion, as evidenced by the burst in speed for India as it approached Eurasia ca. 50 Ma (Schult and Gordon, 1984). Similar behavior is seen in our models (Figs. 4C1, 4D1). Continental motion is a function of the areally integrated basal tractions imparted by mantle flow. Small continents are therefore most easily perturbed by small-scale convective features such as plumes (Phillips and Bunge, 2005). The result is that supercontinent formation is rare in a model with small continents and strong plumes (Fig. 3D).

The best-documented supercontinents, Pangea and Rodinia, suggest by their timing a cycle of a few hundred million years. A stable configuration between 1800 and 1500 Ma was hypothesized for Columbia (Meert, 2002). This indicates that 800 m.y. transpired between the formation of Columbia and that of Rodinia. On the other end of the spectrum, accounting for the brief amalgamation of Pannotia ca. 600 Ma (Dalziel, 1997) leaves only 100 m.y. between it and the demise of Rodinia and 300 m.y. before the formation of the subsequent supercontinent Pangea. Thus, it is likely that Earth's continental aggregation and dispersal history is characterized by an irregular cycle. Since confidence in the geologic data bearing on this issue wanes for those prior to Rodinia, better constraints on the strength of mantle plumes could help further support or confound the notion of a theoretically plausible periodic supercontinent cycle.

ACKNOWLEDGMENTS

This manuscript benefited from thoughtful reviews by G. Davies, L. Lawver, and J. Lowman. We thank L. Gahagan for providing the plate model and assistance used in creating Figure 1. This work was supported by a Charlotte Elizabeth Procter Honorific Fellowship at Princeton University and a Los Alamos National Laboratory Director's Postdoctoral Fellowship (Phillips).

REFERENCES CITED

Anderson, D.L., 1982, Hotspots, polar wander, Mesozoic convection and the geoid: Nature, v. 297, p. 391–393, doi: 10.1038/297391a0.

Baumgardner, J.R., 1985, Three dimensional treatment of convective flow in the Earth's mantle: Journal of Statistical Physics, v. 39, p. 501–511, doi: 10.1007/BF01008348.

Buffett, B., 2002, Estimates of heat flow in the deep mantle based on the power requirements for the geodynamo: Geophysical Research Letters, v. 29, p. 1566, doi: 10.1029/2001GL014649, doi: 10.1029/2001GL014649.

Bunge, H.P., 2005, Low plume excess temperature and high core heat flux inferred from non-adiabatic geotherms in internally heated mantle circulation models: Physics of the Earth and Planetary Interiors, v. 153, p. 3–10, doi: 10.1016/j.pepi.2005.03.017.

Bunge, H.P., Richards, M.A., and Baumgardner, J.R., 1996, Effect of depth-dependent viscosity on the planform of mantle convection: Nature, v. 379, p. 436–438, doi: 10.1038/379436a0.

Condie, K.C., 2004, Supercontinents and superplume events: Distinguishing signals in the geologic record: Physics of the Earth and Planetary Interiors, v. 146, p. 319–332, doi: 10.1016/j.pepi.2003.04.002.

Courtillot, V.E., and Renne, P.R., 2003, On the ages of flood basalt events: Comptes Rendus Geoscience, v. 335, p. 113–140, doi: 10.1016/S1631–0713(03)00006–3.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601, doi: 10.1130/0091–7613(1991)019<0598:PMOLAE>2.3.CO;2.

Dalziel, I.W.D., 1997, Neoproterozoic–Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16–42, doi: 10.1130/0016–7606(1997)109<0016:ONPGAT>2.3.CO;2.

Davies, G.F., 1988, Ocean bathymetry and mantle convection. 1. Large-scale flow and hotspots: Journal of Geophysical Research, v. 93, p. 10,467–10,480.

Donnadieu, Y., Goddéris, Y., Ramstein, G., Nédélec, A., and Meert, J., 2004, A snowball Earth climate triggered by continental break-up through changes in runoff: Nature, v. 428, p. 303–306.

Gable, C.W., O'Connell, R.J., and Travis, B.J., 1991, Convection in three dimensions with surface plates: Generation of toroidal flow: Journal of Geophysical Research, v. 96, p. 8391–8405.

Gordon, R.G., McWilliams, M.O., and Cox, A., 1979, Pre-Tertiary velocities of the continents: A lower bound from paleomagnetic data: Journal of Geophysical Research, v. 84, p. 5480–5486.

Gurnis, M., 1988, Large-scale mantle convection and the aggregation and dispersal of supercontinents: Nature, v. 332, p. 695–699, doi: 10.1038/332695a0.

Gurnis, M., and Davies, G.F., 1986, Numerical study of high Rayleigh number convection in a medium with depth-dependent viscosity: Royal Astronomical Society Geophysical Journal, v. 85, p. 523–542.

Hager, B.H., and Richards, M.A., 1989, Long-wavelength variations in Earth's geoid: Physical models and dynamical implications: Royal Society of London Philosophical Transactions, v. 328, p. 309–327.

Hoffman, P.F., 1991, Did the breakout of Laurentia turn Gondwanaland inside-out?: Science, v. 252, p. 1409–1412, doi: 10.1126/science.252.5011.1409.

Kellogg, L.H., Hager, B.H., and van der Hilst, R.D., 1999, Compositional stratification in the deep mantle: Science, v. 283, p. 1881–1884, doi: 10.1126/science.283.5409.1881.

Kirschvink, J.L., 1992, Late Proterozoic low-latitude glaciation: The snowball Earth, *in* Schopf, J.W., and Klein, C., eds., The Proterozoic biosphere: Cambridge, Cambridge University Press, p. 51–52.

Lawver, L., Dalziel, I.W.D., Gahagan, L.M., Kygar, R., and Herber, B., 2004, The plates 2004 atlas of plate reconstructions (750 Ma to present day): Plates Progress Report No. 290–0804: University of Texas Technical Report 191, 108 p.

Li, Z.X., Evans, D.A.D., and Zhang, S., 2004, A 90º spin on Rodinia: Possible causal links between the Neoproterozoic supercontinent, superplume, true polar wander and low-latitude glaciation: Earth and Planetary Science Letters, v. 220, p. 409–421, doi: 10.1016/S0012–821X(04)00064–0.

Lowman, J.P., and Gable, C.W., 1999, Thermal evolution of the mantle following continental aggregation in 3D convection models: Geophysical Research Letters, v. 26, p. 2649–2652, doi: 10.1029/1999GL008332.

Lowman, J.P., and Jarvis, G.T., 1999, Effects of mantle heat source distribution on continental stability: Journal of Geophysical Research, v. 104, p. 12,733–12,746, doi: 10.1029/1999JB900108.

Meert, J.G., 2002, Paleomagnetic evidence for a Paleo-Mesoproterozoic supercontinent Columbia: Gondwana Research v. 5, p. 207–215, doi: 10.1016/S1342–937X(05)70904–7.

Moores, E.M., 1991, Southwest U.S.–East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428, doi: 10.1130/0091–7613(1991)019<0425:SUSEAS>2.3.CO;2.

Nolet, G., Karato, S.I., and Montelli, R., 2006, Plume fluxes from seismic tomography: Earth and Planetary Science Letters, v. 248, p. 685–699, doi: 10.1016/j.epsl.2006.06.011.

Phillips, B.R., and Bunge, H.P., 2005, Heterogeneity and time dependence in 3D spherical mantle convection models with continental drift: Earth and Planetary Science Letters, v. 233, p. 121–135, doi: 10.1016/j.epsl.2005.01.041.

Rogers, J.J.W., and Santosh, M., 2002, Configuration of Columbia, a Mesoproterozoic supercontinent: Gondwana Research v. 5, p. 5–22, doi: 10.1016/S1342–937X(05)70883–2.

Schult, F.R., and Gordon, R.G., 1984, Root mean square velocities of the continents with respect to the hot spots since the Early Jurassic: Journal of Geophysical Research, v. 89, p. 1789–1800.

Sutton, J., 1963, Long-term cycles in the evolution of the continents: Nature, v. 198, p. 731–735, doi: 10.1038/198731b0.

Trubitsyn, V.P., and Rykov, V.V., 2001, A numerical evolutionary model of interacting continents floating on a spherical Earth: Russian Journal of Earth Science, v. 3, p. 83–95.

Turcotte, D.L., and Schubert, G., 2002, Geodynamics: New York, Cambridge University Press, 456 p.

Wasserburg, G.J., MacDonald, G.J.F., Hoyle, F., and Fowler, W.A., 1964, Relative contributions of uranium, thorium, and potassium to heat production in the Earth: Science, v. 143, p. 465–467, doi: 10.1126/science.143.3605.465.

Wegener, A., 1924, The origin of continents and oceans [translated from the third German edition by J.G.A. Skerl]: London, Methuen & Co., 212 p.

Yoshida, M., Iwase, Y., and Honda, S., 1999, Generation of plumes under a localized high viscosity lid in 3-D spherical shell convection: Geophysical Research Letters, v. 26, p. 947–950, doi: 10.1029/1999GL900147.

Zhao, G., Cawood, P.A., Wilde, S.A., and Sun, M., 2002, Review of global 2.1–1.8 Ga orogens: Implications for a pre-Rodinia supercontinent: Earth-Science Reviews, v. 59, p. 125–162, doi: 10.1016/S0012–8252(02)00073–9.

Zhong, S., and Gurnis, M., 1993, Dynamic feedback between a continentlike raft and thermal convection: Journal of Geophysical Research, v. 98, p. 12,219–12,232.

Manuscript received 25 January 2007
Revised manuscript received 30 April 2007
Manuscript accepted 3 May 2007

Printed in USA